Development and prospects of the D-Start simplest pulse engines for single-pulse maneuvers of ultralight femto-class spacecrafts with external energy sources (including the possibility of using space debris)

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It is proposed to development of engines with external energy sources for single-pulse interorbital maneuvers of ultra-small femto-class spacecrafts and a family of related technical solutions. It is planned to develop the possibility of cost-effective use of space debris and waste from technological processes in engines. Experimental equipment was developed and manufactured. Materials with a high gasification rate for the active targets of the engines are selected. The efficiency of the selected technical solutions in conditions identical to the conditions of open space is confirmed. A series of real-mode ground tests is underway and a series of flight tests are planned for end of 2021.

I. INTRODUCTION

Mastering the design and production of the lower part of the line of ultra-small spacecrafts [1] with a unit mass of 100 g or less-pico- and femto-classes, including case-free spacecrafts "on board" (such as ChipSat) [2], with the cost of manufacturing the spacecraft and its launch proportional to its mass, opens up opportunities for significantly more cost-effective solutions to most problems of space exploration, development and use than the use of traditional means, and prospects for solving new problems.

The extremely low cost of such ultra-small spacecrafts (from several thousand rubles for a single spacecraft and from several tens of thousands of rubles for a launch, or from tens to hundreds of US dollars) opens up the possibility of participation in space activities of new participants with a limited budget-legal entities and individuals.

The main problem that limits the scope of such spacecrafts is the lack of propulsion systems that allow them to perform independent maneuvers. Currently, a batch launch of modern ChipSat spacecrafts in the amount of 100-200 is carried out in a CubeSat 3U launch container [2], the mass of which can exceed the mass of the entire group of femtosatellites, and data collection and transmission of such spacecraft after removal from the container is carried out from a small area near the container.

Currently, electrodynamic propulsion systems using the Lorentz force [4, etc.] and solar sails integrated into the design of the femtosatellites [5, etc.], as well as laser sails, are proposed for femtosatellites [3]. They primarily relate to constant micro-thrust engines for maintaining a constant altitude of a femtosatellite in low-Earth orbit.

At the same time, there is the problem of space debris, the relevance of which increases with the growth of the number of spacecraft in general, including ultra-small spacecraft. Known projects of debris disposal in spacecraft engines ([6], etc.). The cost of these engines per unit of thrust or mass of the spacecraft is not determined, but is significantly higher than for engines of traditional designs. Their design and technology exclude the possibility of their miniaturization for use on femto-spacecrafts and the using of small space debris.

It can be noted that other well-known projects for the active removal of space debris that do not involve its use in engines are unprofitable and economically inefficient, and are in no way related to solving the problem of maneuvering ultra-small spacecrafts.

II. PROBLEM STATEMENT

In this regard, the task was set to development of sufficiently simple and efficient engines for a femto-class spacecrafts with external energy sources, providing in the future the possibility of using space debris as an energy source, as well as other external energy sources.

A family of technical solutions based on the technology and structural elements of rocket engines with external energy sources for single-pulse spacecraft maneuvers is proposed.

Variants of the main design elements of hypothetical high-power pulsed engines are used – including the so-called kinetic jet engines (KJE) in the "kinetic sail" version, the high-power nuclear pulsed rocket engine "Medusa" by J. Solem [7] and G. Matloff's high-thrust solar sails [8] – adapted to structurally and technologically simple small-size structures.

As a basic technical solution, we consider KJEs using space debris as an energy source. The concept was first presented in the ICI RAS in 2019 [9]. In order to simulate and develop the working process and design of engines in real conditions, in 2020 by Dmitry Novoseltsev was organized a small scientific and technical innovation enterprise startup D-Start, which performs a number of works on the creation of these engines – including: preparation and implementation of a series of ground-based experiments "Impact" (including R&D "Development and testing of prototypes of a kinetic jet engine with a working process due to the utilization of the kinetic energy of space debris. Development and testing of an experimental target model of the prototype engine", carried out at the expense of a grant from the Russian Foundation for the Promotion of Innovation, FASIE and a planned series of flight experiments on the ISS - "Impulse-0", "Origami", "Firework" - in 2020-2021.

III. THEORY

The theory of the working process of the KJE in a counter collision with a kinetic impactor is presented in a report in the ICI RAS 2019 [9] and the application for the patent of invention "Method of performance of a kinetic jet engine" [12].

As noted [9],, the using of the kinetic energy of space debris (as impactors) at typical collision speeds of about 10 km / s [11] requires a high target gasification rate to ensure the completion of the working process within the working volume of the engine reflector. In this regard, the materials used as part of the elements of the spacecrafts detonation automation with a detonation combustion speed of more than 7 km/s were selected as model materials for the active targets of the engine prototypes for working out the working process [10].. In this case, the working process of the engine during a single-pulse maneuver is provided by the chemical-kinetic explosion of the target in a counter collision with the impactor.

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Under a number of assumptions (including the assumption of complete gasification of the target and complete absence of gasification of the impactor), the velocity increment ΔV, m/s of the spacecraft mass M, kg is:

$$\Delta V = \frac{25}{24\,M}\sqrt{\frac{2}{5}m_t\,(E_i + E_t)}$$

where the indices i and t refer to the impactor and the target, respectively.

E_i and E_t, J are, respectively, the kinetic energy of the impactor with a mass of m_i, kg and the chemical energy of the target with a mass of m_t, kg:

$$E_i = \frac{m_i V_i^2}{2}$$

$$E_t = m_t H_t$$

where H_t, J/kg is the lowest specific heat of combustion (heat of explosion) of the target material.

At the characteristic collision velocity of the impactor with the target of the order of 10...13 km/s [11], the specific kinetic energy of the collision E_i/m_i will be (5.0...8.5)x10^8 J/kg, which significantly exceeds the specific heat of combustion of traditional chemical rocket fuels of the order of 10^7 J/kg

IV. EXPERIMENTAL RESULTS

Since the processes in the engines under consideration are high-energy and fast-flowing ($10^{-6}…10^{-5}$ s), their modeling is quite a difficult task. According to the technical specifications of D-Start LLC, was developed and manufactured a mobile test bench MSID for engines consisting of a thermal vacuum chamber, an optional bench low-speed throwing device, and a control system for recording and processing measurements. In February 2021 the stand was put into operation, experimental studies of the structural elements of the prototype engine for the series of experiments "Impact", as well as existing models of structural elements for the flight experiments "Firework", "Origami", "Impulse-0" in conditions simulating near-Earth space (vacuum, radiant heating by thermal radiation within the solar constant of 1.37 kW/m^2) were performed. During the tests, the operability of the elements was confirmed at a rarefaction of up to 2 Pa (absolute) and temperature up to 150 ◦C, high-speed video recording and instrument registration capabilities.

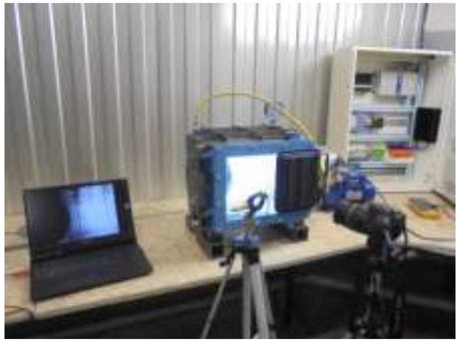

Fig. 1. Experiment at the MSID stand
(tests of the model reflector and target suspension, models "Firework", "Origami", "Impulse-0")

V. DISCUSSION OF THE RESULTS

The available equipment and methodological base of D-Start LLC allow you to carry out studies of the working process of engines, as well as elements attached to the reflector and the target suspension, in conditions close to real operating conditions.

In mid-2021, it is planned to conduct a series of experiments "Impact" ("Impact-GPM") in accordance with the program and methodology and technical specifications of D-Start on the basis of "TsNIIMash" JSC using the GPM throwing system, with the throwing of impactors made of aluminum alloys, simulating small fragments of space debris, at a target made of a detonation material , at a speed of up to 4...7 kilometer per second.

In order to test the deployment of compact engine design elements (reflector, suspension) in the experiments "Firework", "Origami", and the current model of the kinetic engine without using a target made of high - energy materials-the sublimation low-thrust engine "Impulse" for the ChipSat femtosatellite (with the possibility of subsequent deorbiting) on the mass – dimensional model of the femtosatellite in the experiment "Impulse-0" - the coordination of these experiments is underway in the summer of 2021 on the ISS during the extravehicular activity of the crew.

With satisfactory results of flight experiments, at the end of 2021, flight tests of the Impulse engine are planned on the company's own D-Start femtosatellite AmbaSat-1 manufactured by AmbaSat Ltd to change the parameters of its orbit relative to a group of similar femtosatellites during their container launch.

VI. CONCLUSIONS

The results obtained confirm the possibility of developing and producing in the nearest future a family of simple engines for single-pulse maneuvers of a mass – availability femto spacecrafts, and in the more distant future - the development of rational utilization of space debris as an energy carrier in them.

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